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A Collision Warning System for rear-end collision: a driving simulator study

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Abstract

Collision warning and collision avoidance systems are emerging automotive safety technologies that assist drivers in avoiding rear-end collisions. Their function is to allow the driver enough time to avoid the crash and yet avoid annoying the driver with alerts perceived as occurring too early or unnecessary. The aim of this paper was analyzing the driver's behavior in order to define effective driver assistance systems which can be readily accepted by the driver. A study was performed with an interactive fixed-base driving simulator. A sample of 32 drivers drove on a two-lane rural road. Four different driving traffic conditions were implemented. The data recorded during the tests were analyzed to assess the safety distances required by the driver during a car-following situation. Based on the risk perception of the driver a new collision warning algorithm was developed.

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Keywords: Collision Warning; Rear-end collisions; Driving simulator

1. Introduction

Road safety is certainly one topic of great interest that concerns the whole community at national, European and global level. Several studies have been conducted to improve road safety and reduce the number of accidents on the roads. In particular, a common goal was set in 2001 at European level to halve the road accident victims by 2010. Different instruments have been set up in order to achieve this objective, such as education campaigns, use of driver assistance systems in the vehicle and the design of safer transport infrastructure through an automated network in constant communication with all elements of the road. The occurrence of an accident must take into account the key variables that constitute the whole road system: the road, the driver, the vehicle and the environment. Among these, a significant role is played by the driver and the vehicle. Based on the results of recent research on the causes of accidents, human error comes into play in almost 93% of accidents and is the only cause of accidents in about three quarters of cases (Commission of the European Communities Brussels, 2006).

The total number of accidents can be reduced through the safety systems installed in vehicles. However, it was found that many "traditional" (or passive) safety measures (such as seat belts, airbags, etc.) are reducing their

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effectiveness. It is therefore unlikely that they will bring further improvements in safety at reasonable cost. Passive safety systems therefore have to be complemented by introducing on the market more advanced safety features in vehicles (Commission of the European Communities Brussels, 2003), i.e. active and collaborative systems. With regard to this, there are already on the market driver assistance systems in the vehicle, designed to provide the driver with a valid support to assess non-evident risk situations, thus limiting the driving errors. In order to maximize their effectiveness, these systems should be primarily shared by the driver, i.e. the system should provide warnings in situations of “real” risk, for which the driver takes corrective action of his/her motion (e.g. deceleration). Too frequent and too early alarms could be interpreted as “an annoyance” and ignored by the driver to the point of bringing him/her to decide to turn off the device. In this case, the system would clearly not serve the purpose for which it has been designed. In the design of active systems, it is therefore of utmost importance to find a proper balance between not alerting too early, and yet to secure enough time of reaction, i.e. as to leave the driver the right time and adequate space to avoid a possible collision or at least reduce the severity of the potential impact. The present work was undertaken in this context, and it has the objective to analyze the driver’s behavior to contribute to define driver assistance systems which are calibrated on the driver’s behavior and therefore can be readily accepted by the driver.

Many advanced driver assistance systems (ADAS) exist and they allow investigating a wide number of parameters and maneuvers (lateral control, longitudinal control, parking and reversing aids, vision enhancement, driver monitoring, pre-crash systems, road surface or low-friction warning) (Lundgren and Tapani, 2006). As the driving assistance systems act when it is still possible to avoid the accident, or significantly reduce its severity while maintaining the high level of attention of the driver, the notice or the intervention in critical situations could help to significantly improve road safety. This is very important because wrong driving behaviors, distracted driving and excessive speed are among the main causes of accidents. We chose to focus on the analysis of driver behavior in car-following as the majority of road accidents is between two or more vehicles. Furthermore, the most common type is the front-side crash, followed by rear-end collisions. Therefore these are the situations of greatest risk.

In particular, in this study we analyzed tests conducted using the driving simulator of the Inter-University Research Centre for Road Safety (CRISS) site in the University of Roma TRE. The driver behavior during car-following was then considered in order to assess the accepted risk rear-end collisions. Various studies have shown that observations derived from driving simulators are a reliable source of data to examine drivers’ behavior and the assessment of rear-end collision risk (Alicandri, 1994; Bella, 2009; Farah et al., 2009; Jenkins and Rilett, 2004; Broughton et al. 2007), or to analyze the efficiency of driver assistance systems (Cheng et al. 2002; Abe and Richardson, 2005; Jamson et al, 2008). That because advanced-interactive driving simulators provide a high degree of realism, allow experiments to be conducted in controlled conditions and assure the highest degree of safety for test drivers.

The study was developed through the following steps:

- analysis of methods and algorithms found in the literature on driver assistance systems;
- driving simulation study to record the driver behavior during car-following situations;
- analysis of data from simulated driving;
- development of a new algorithm based on driver behavior for a driver assistance system.

2. Background

Longitudinal collision avoidance technologies address rear-end collisions, which are usually due to the difficulty for the driver to react to a sudden braking by the leading vehicle. A collision avoidance system operates in the following manner: a sensor installed at the front of a vehicle constantly scans the road for vehicles. When one is found, the system determines whether the vehicle is in imminent danger of crashing, and if so, a warning is issued, or a collision avoidance maneuver is undertaken. The typical criteria for activation of collision avoidance are:

- *Worst-case scenario*: the system assumes that the lead vehicle could brake at full braking power at any time. In essence, it maintains a “safe distance”, i.e. the minimum distance necessary to come to a stop in the event the leading car suddenly brakes.
- *Time-to-collision (TTC)*: the system determines the time required for two vehicles to collide if they continue at their current speed and on the same path (assuming that V_F is greater than V_L).

The Figure 1 shows a car-following situation and the considered variables.

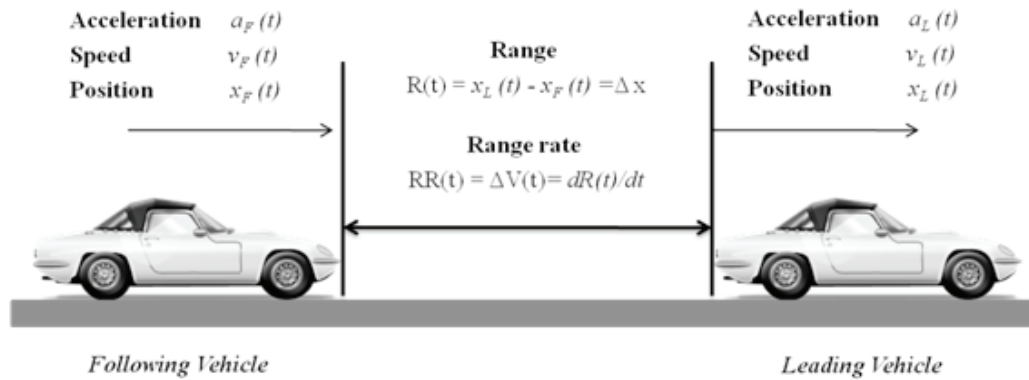


Figure 1 The car-following situation: variables of interest

As reported by the literature, several algorithms have been developed to activate the Collision Warning Systems and in particular the two main types are based on kinematic and perceptual approach. Whatever the criterion of activation, however, there are two major challenges: the system must be reliable and functional, secure and shared by the driver (i.e. it should give few false alarms). In the following sections we analyze these two different approaches, which are based on different assumptions and therefore operate in different ways.

2.1. Kinematic approach

The algorithms based on kinematic trigger alerts use the fundamental laws of motion. Combining the hypothesis of the deceleration and reaction time with the current state of a vehicle, the algorithm determines a minimum distance required to stop safely. When the vehicle is at a distance minor or equal to the safe distance from another vehicle, an alarm is triggered. The kinematic approach starts the warning based on the criterion of the worst case.

From a thorough exam of the existing literature (Ararat et al., 2006; Brown et al., 2001; Jamson et al., 2008; Kiefer et al., 1999; Kiefer et al., 2003; Kiefer et al., 2005; Lee and Peng, 2005; Martinez and Canudas-de-Wit, 2007; Seiler et al., 1998; Zhang et al., 2006), we grouped different algorithms that evaluate on the basis of kinematic laws of motion the critical warning distance (R_{warning}) for Collision Warning (CW). These algorithms calculate a threshold distance based on vehicle motion and the variables related to human characteristics (vehicle speed, acceleration, delay in the human response, etc.). When the distance is smaller than the limit value calculated according to the type of system used, an alarm is activated. The Table 1 shows the equations and terms most frequently used in CW systems.

Table 1 Frequently used equations and terms in CW Systems

Meaning	Form
Following vehicle stopping distance (R_F)	$R_F = 0.5 v_F^2 / (-a_F)$, $a_F < 0$, $v_F \geq 0$
Leading vehicle stopping distance (R_L)	$R_L = 0.5 v_L^2 / (-a_L)$, $a_L < 0$, $v_L \geq 0$
Reaction time margin (R_{td})	$R_{td} = \tau v_F$, $v_F, \tau_F > 0$
Range rate margin (R_{RR})	$R_{RR} = \tau v_{rel}$, $\tau > 0$, $v_{rel} > 0$
Minimum range (R_{min})	$R_{min} = \text{constant} > 0$

where $v_{rel} = \Delta V$ is the relative speed between the following and leading vehicles in m/s. For the other parameters see Figure 1.

The main types of kinematic algorithms found in the literature are described below.

2.1.1. The Mazda Algorithm

The algorithm developed by Mazda considers a hypothetical worst case. The scenario assumes that initially the two vehicles maintain constant speeds: V_L and V_F . Subsequently, the lead vehicle starts to brake after time τ_2 with a deceleration rate α_L , while the host vehicle starts to brake after an additional time τ_1 at deceleration rate α_F , which continues until both vehicles come to a full stop. The algorithm shown below calculates the minimum space required to ensure that the scenario described above occurs without collisions.

$$R_{\text{warning}} = f(v_L, v_F, v_{\text{rel}}) = 0.5 [(v_F^2 / \alpha_F) - (v_L^2 / \alpha_L)] + v_F \tau_1 + v_{\text{rel}} \tau_2 + R_{\text{min}} \quad (1)$$

where R_{min} is the minimum range (see Figure 1 and Table 1). The distance calculated by this formula must be taken as a critical warning distance (Ararat et al., 2006). The values of the variables are reported in Table 2.

2.1.2. The Stop Distance Algorithm (SDA)

This algorithm defines a warning distance based on the difference between the stopping distances of the leading and following vehicles. If the distance between the two vehicles is minor than the warning distance, an auditory collision warning alarm is presented to the driver. The following describes the logic activating the alarm:

$$R_{\text{warning}} = f(v_L, v_F) = v_F \tau_{\text{driver}} + (v_F^2 / 2\alpha_F) - (v_L^2 / 2\alpha_L) \quad (2)$$

where τ_{driver} is the driver's reaction time. The values of the variables are reported in Table 2.

2.1.3. The PATH (Berkeley) Algorithm

This algorithm is a modified version of Mazda's algorithm. The critical warning distance is given by:

$$R_{\text{warning}} = f(v_L, v_F) = 0.5 [(v_F^2 / \alpha) - (v_L^2 / \alpha)] + v_F \tau + R_{\text{min}} \quad (3)$$

According to this algorithm, the leading vehicle brakes at the maximum deceleration rate α , while the following vehicle starts to brake after reaction time τ at the same deceleration. R_{warning} is the minimum distance required to avoid collisions until both vehicles come to a full stop. The values of the variables are presented in Table 2.

Table 2. Parameter values for algorithms

	α_F (m/s ²)	α_L (m/s ²)	τ_1 (s)	τ_2 (s)	τ_{driver} (s)	τ (s)	R_{min} (m)
Mazda	6	8	0.1	0.6	-	-	5
SDA	5	5	-	-	1.5	-	-
PATH	6	6	-	-	-	1.2	5

2.1.4. CAMP FCW project

Another very interesting model was proposed by Kiefer et al. (Kiefer et al., 1999; Kiefer et al., 2003; Kiefer et al., 2005). Drivers were asked to execute last-second braking and steering maneuvers while approaching a surrogate target lead vehicle. Based on the data recorded on field, the CAMP Forward Collision Warning (FCW) system was defined. It determines the alert range necessary to assist the driver to avoid a potential crash, which is a function of speeds and decelerations of the vehicles (leading and following) and total delay time. Total delay time was the composite sum of three separate delay times: the interface delay time, the driver brake delay and the brake system delay time. The interface delay time is defined as the time between when the crash alert criterion was violated and when the crash alert was presented to the driver. This delay is assumed to be 0.18 s. The driver brake delay is defined as the time between crash alert onset and when the driver triggered the brake switch. This delay was assumed to be 1.50 seconds for surprise alerts (Olson and Sivak, 1996). The brake system delay time is defined as the time between braking onset and vehicle slowing and is assumed to be 0.20 s. The total delay time is therefore equal to 1.88 s.

$$R_{\text{warning}} = f(v_L, v_F, \alpha_L, \alpha_F, \text{Total Delay Time}) = ((v_F - v_L) (\text{Total Delay Time}) + 0.5 (\alpha_F - \alpha_L) (\text{Total Delay Time})^2) + ((v_F + (\alpha_F (\text{Total Delay Time}))) - (v_L + (\alpha_L (\text{Total Delay Time}))))^2 / (-2((-1.61 + 0.668 (\alpha_L) - 0.807 (v_F - v_L) + 0.765) - \alpha_L))) \quad (4)$$

2.2. Perceptual approach

With algorithms based on the perceptual approach, an alarm is triggered based on thresholds of perception. When the human perceptual threshold is exceeded, a signal is activated to alert the driver. This approach is based on thresholds of Time to Collision (TTC). The TTC is considered as one of the most widely used safety indicators and a measure of a crash risk. It is defined as the time until a collision between two vehicles would have occurred if the collision course and speed difference were maintained (Minderhoud and Bovy, 2001). The original definition was coined by Hayward in 1972 (Hayward, 1972).

$$TTC = (x_F - x_L - l_F) / (v_F - v_L) \quad (5)$$

where l_F is the length of the following vehicles; for the other variables see Figure 1.

The TTC is only calculated if the following vehicle's speed is greater than the one of the leading vehicle ($v_F > v_L$). In particular, low TTC indicate a higher risk of collision. Usually, thresholds value for the TTC are set to trigger a warning, also called a critical value. The threshold value in the literature ranges between 5 and 2 seconds (Minderhoud and Bovy, 2001). The main types of perceptual algorithms found in the literature are described below.

2.2.1. The Honda Algorithm

According to Honda's algorithm, a warning is issued when the TTC is equal to 2.2 seconds. The distance is calculated by means of:

$$R_{\text{warning}} = f(v_{\text{rel}}) = 2.2 v_{\text{rel}} + 6.2 \quad (6)$$

where 6.2 is an additional safety value.

2.2.2. The Honda's Collision Mitigation Braking System (CMBS)

Another system by Honda, called Collision Mitigation Braking System (CMBS), is based on the evaluation of the TTC. This system returns three different alerts. There is an initial phase of attention if the distance between the following and leading vehicles exceeds the safety limit, estimated with a threshold of TTC equal to 3 seconds. When this threshold is exceeded, an alarm starts to suggest the driver to take preventive measures to avoid collision. After this, there are other phases of prevention and action that are activated if the distance continues to gradually decline, i.e. TTC less than 2 seconds and less than 1 second respectively. In both cases the aim is to reduce the severity of impact, but the collision will hardly be avoided.

2.2.3. The Hirst&Graham Algorithm

Many criticisms have been reported in the literature on the validity of the assumption of a constant threshold value of the TTC to distinguish between safe and unsafe situations. It is often suggested to investigate if and how this parameter varies depending on speed (Sultan and McDonald, 2003). In relation to the possible link between the TTC and speed, it is worth mentioning a perceptual-based algorithm developed by Hirst and Graham (1997). They suggest that a TTC-based warning should be increased with a speed penalty (SP) to achieve appropriately timed warning. They suggest that this type of algorithm would minimize nuisance alarms. In essence, the algorithm developed uses a threshold set at 3 seconds of the TTC, with an adjustment for the vehicle speed (SP) equal to 0.4905 m for each kilometer per hour of the following vehicle speed:

$$R_{\text{warning}} = f(v_{\text{rel}}, v_F) = 3 \, dR/dt + 0.4905 v_F \quad (7)$$

where $dR/dt = \Delta V$ is the relative speed between two vehicles.

3. Method

A laboratory experiment using a driving simulator was developed in order to collect data on drivers' car-following behavior. The driving simulator of the Inter-University Research Centre for Road Safety (CRISS) in the University of Roma TRE was used.

3.1. CRISS Driving Simulator

The CRISS simulation system is an interactive fixed-base driving simulator. It includes a complete vehicle dynamics model based on the computer simulation Vehicle Dynamics Analysis Nonlinear. The model has been adapted to run in real time and it has been validated extensively (Allen et al, 1998). Four computers are networked and three interfaces (steering wheel, pedals and gearshift lever mounted on a real vehicle to reproduce a realistic driving environment) constitute the hardware. A computer processes the equations of motion while the others produce pictures. The driving scene is projected on three screens (see Figure 2 a). The usual field of view is 135° . The resolution of the visual scene is 1024×768 pixels and the refresh rate is 30 to 60 Hz depending on the complexity of the scene. The sound of the engine is reproduced through a sound system.

It is possible to implement different traffic scenarios: kinds of vehicles, numbers of vehicles for lane, speeds and path of each vehicle. A set of parameters can be recorded to describe travel conditions (vehicle barycentre, relative position in relation to the road axis, local speed and acceleration, steering wheel rotation angle, pitching angle, rolling angle, etc.). The system also allows us to record the time and distance from the leading vehicle, as well as time and distance from the vehicle in the opposite direction. All data can be recorded in intervals of time (a fraction of a second) or space (a meter). Figure 2 shows the workstation for the design and implementation of the scenarios in the simulator and a phase of a driving.

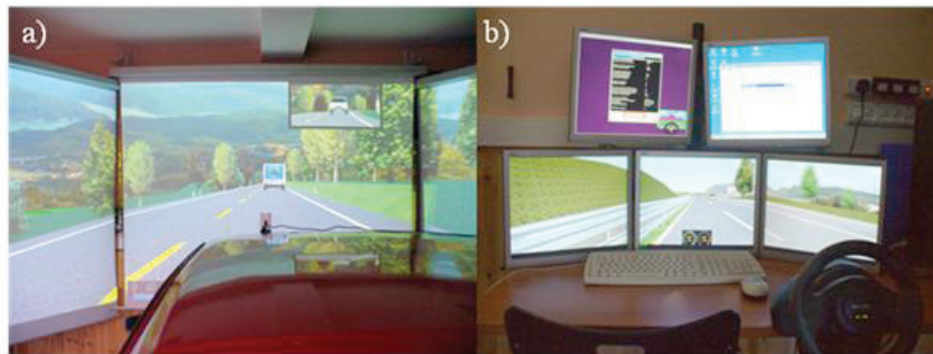


Figure 2. CRISS Driving Simulator: a) phase of the experiment b) workstation for the implementation of the scenarios

3.2. Test Alignment

An alignment of a two-lane rural road was designed and implemented in the driving simulator. The alignment was 8.5 km long and had a cross-section 10.5 m wide (lane and shoulder widths were 3.75 m and 1.5 m respectively). The alignment was divided into tangents with length ranging between 200 m and 1000 m and horizontal curves made up of approach clothoid, circular curve and departure clothoid. The radii of the circular curve ranged between 215 m and 1000 m. The traffic was introduced in both directions. Four scenarios were simulated with a growing total traffic volume, ranging between 350 veh/h (scenario 1) and 900 veh/h (scenario 4), in order to simulate four different volume-to-capacity ratios (N/C), ranging between 0.18 and 0.47. The speed of vehicles changed in the four scenarios. In particular, in the opposite direction of the driver values between 85 and 70 km/h were given, while for vehicles traveling in the same direction of the driver the speed values were constant and they varied between 75 km/h (in scenario 1) and 60 km/h (in scenario 4).

3.3. Procedure and participants

The study was carried out using dry pavement conditions in good state of maintenance, simulating the characteristics of a medium-class car, both with regard to size and mechanical performance, with automatic gear-changes. The data recording system was set to acquire all the parameters at spatial intervals of 5m.

The driving procedure was broken down into the following steps: 1) the driver is instructed on the duration of the driving and the use of the steering wheel, pedals, and automatic gear; 2) the driver is trained in the driving simulator on a specific alignment for approximately 10 min, so that he/she becomes familiar with the simulator's control instruments; 3) the execution of two test scenarios in the established sequence; 4) the driver gets out of the car for about 5 minutes in order to re-establish psychophysical conditions similar to those at the beginning of the test and fills in a form with personal data, years of driving experience, average annual distance driven; 5) the execution of the two remaining test scenarios in the established sequence; 6) the driver fills in an evaluation questionnaire about type (nausea, giddiness, daze, fatigue, other) and entity (null, light, medium, and high) of the discomfort perceived during the driving. The sequence of the four scenarios was counterbalanced in order to avoid influences due to the repetition of the same order in the experimental conditions. Drivers were instructed to drive as they would normally do in the real world.

The simulation was performed by 32 drivers aged from 22 to 40, male (70%) and female (30%), with a driving experience of at least 3 years and an average annual driven distance on rural roads of at least 2,500 km. From the analysis of the questionnaire filled in by the drivers at the end of the test, it emerged that no participant experienced any high or medium level of discomfort, 13 and 19 participants experienced light and null level of discomfort respectively. Therefore no participant was excluded from the sample.

3.4. Data Processing

The data (longitudinal speed, distances between vehicles and their relative speeds) collected during the simulations were analyzed to assess the conditions in which the driver adopts "evasive maneuvers" of car-following such as overtaking maneuver or slow down to increase the spacing from the leading vehicle. The data were recorded under these conditions:

- at the beginning of overtaking maneuver (only the accelerative maneuvers were considered);
- at the minimum spacing, during the car-following maneuver.

475 of these driving conditions were observed and then analyzed; 315 were overtaking and 160 were car-following maneuver.

Figure 3 shows an example of the range between two vehicles in a car-following situation. In particular D_{driver1} and D_{driver3} refers to the first condition (overtaking maneuver; the vehicle which follows approaches the vehicle in front, queues maintaining a constant speed and then overtakes), while D_{driver2} refers to the second one (minimum spacing, during the car-following maneuver; the driver approaches vehicle in front, comes to a minimum distance and then decelerates in order to increase the distance from it). These distances, called D_{driver} , were used for the analysis.

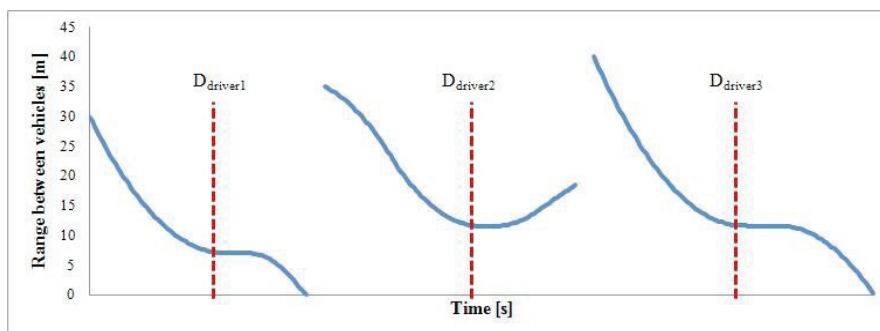


Figure 3. Example range between vehicles profile of a car-following situation

In order to define an acceptable alert timing zone D_{driver} should be added to a covered distance in the “drive brake delay” which is defined as the time between crash alert onset and brake switch by the driver. In other words the warning system should provide an alert Δt in advance compared to time when the driver is at the minimum spacing from the lead vehicle. Based on experimental studies Kiefer ((Kiefer et al., 1999) suggest values of Δt equal to 1.18 s and 1.52 s (Figure 4).

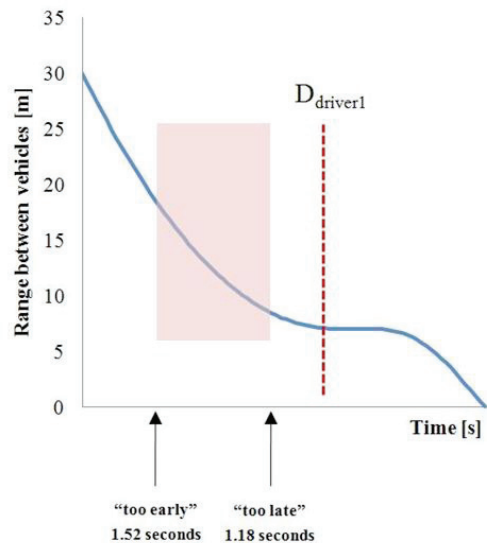


Figure 4. Alert timing zone

The onset of the FCW crash alert must occur at any point within a crash alert timing zone, where this zone is defined by “too early” and “too late” onset range cut-offs (or bounds) (Kiefer et al., 1999).

4. Results

4.1. Development of a new algorithm based on driver behavior

A statistical analysis was conducted to obtain a new collision warning algorithm that reflects the car-following driver behavior during simulator testing. The multiple linear regression technique was used in model estimation. The following model was found.

$$d = f(\Delta v, v_F) = 1,25\Delta v + 1,55 v_F \quad R^2 = 0.89 \quad (9)$$

where Δv and v_F are expressed in m/s.

The distance (d) given by the model can be considered as a threshold which should trigger an alarm system for driver assistance. A such alarm is provided when the driver is in the middle of the crash alert timing zone (in other words when Δt is 1.35s). The independent variables used in the model were significant at the level of 5%. The model is consistent as the distance to which the drivers take evasive maneuvers of the car-following condition, increases as the speed of the driver (v_F) and the relative speed between the following and leading vehicle (Δv) increases. It is a model with perceptual calibration system. It can be considered quite similar to the system of Hirst and Graham (1997) (see equation 7) and but it provides different coefficients that reflect better the drivers' behavior.

The new proposed algorithm was compared to algorithms reported in the literature. The performance of the various models was studied by setting different values of speed of the driver (in a range between 100 km/h to 60 km/h). It should be noted that the range of the distances given by the different models is quite wide (Fig. 5). That because the assumed hypotheses for developing the models are quite different .

The algorithm developed in this study resulted less precautionary (gives lower distances) than SDA for all values of analysed speed (Fig. 5 a, b). As shown in Fig. 5, the new algorithm always provides higher values than the

CMBS-TTC 3s, Honda and CAMP.

For driver's speed equal to 100 km/h (see Figure 5 a) the distances returned by the model are always higher than those provided by the Hirst&Graham's model; distances are higher than those returned by the PATH model for ΔV up to 12 km/h, and by the Mazda model for ΔV up to 41 km/h. However, it must be noted that values of ΔV higher than 30 km/h are rarely found on a rural two lanes road, in the conditions considered.

For driver's speed equal to 60 km/h (see Figure 5 b), the new model is always more precautionary (gives higher distances) than Mazda model. The same applies with regard to PATH model for ΔV up to 23 km/h (a more similar pattern is observed afterwards), and to Hirst&Graham's model for ΔV up to 36 km/h.

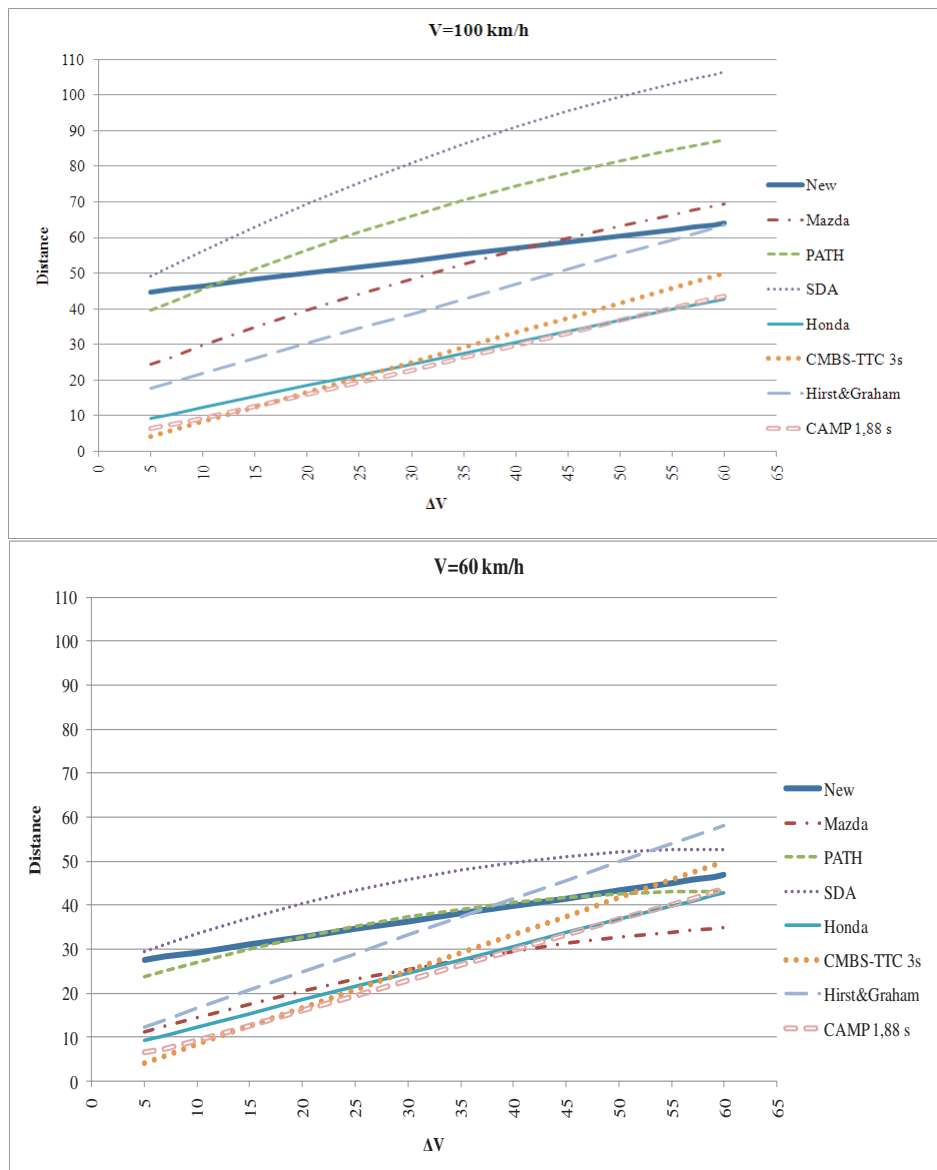


Figure 5. New algorithm compared with the warning distances of the literature: a) speed of driver (V) of 100 km/h; b) speed of driver (V) of 60 km/h

5. Conclusions

The experimental study carried out at the CRISS driving simulator was aimed to analyze the driver behavior during car-following maneuvers. Based on data collected in 475 car-following conditions a new collision warning algorithm was defined. The distance given from the proposed model can be considered as a threshold which should trigger an alarm system for driver assistance in order to advise the driver when he is in the crash alert timing zone. The proposed algorithm reflects the real risk perception by drivers. Therefore it should minimize false alarms and should help to avoid a potential collision.

Further studies are needed to validate the proposed algorithm (expand the database available in terms of drivers and traffic types, several values of deceleration of the leading vehicle, etc.). It is planned in future research to implement in the driving simulator a driver assistance system based on the algorithm proposed in order to test its effectiveness.

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